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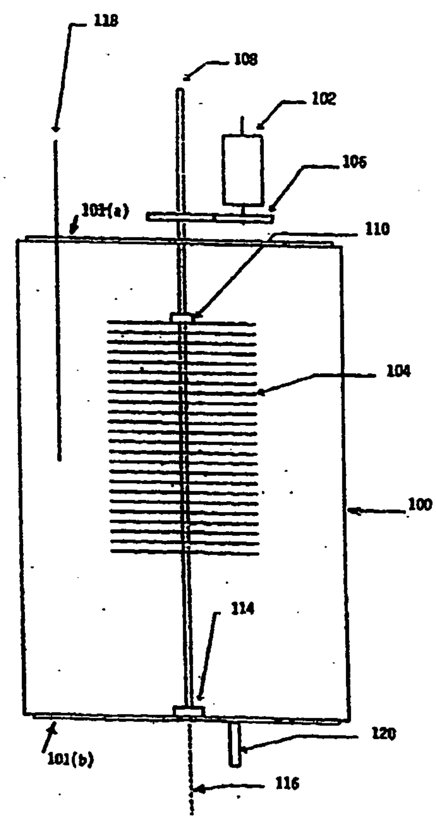
(54) Title: LIQUID BREATHING-GAS EXCHANGER

(57) Abstract

In accordance with the present invention there are provided devices and methods for facilitating the transfer of gas between liquid and gas phases. Invention devices and methods employ fluid dispersion units that cast liquid in the form of discrete thin planar layers. In this manner, the liquid assumes a dispersion of droplets which, owing to their size-to-volume ratio, allow for efficient mass transfer between the gas and liquid phases. Invention devices and methods find particular application in the field of liquid ventilation, wherein a patient is exhausting carbon dioxide and obtaining oxygen through a partially or completely liquid medium such as a perfluorocarbon.



LIQUID BREATHING-GAS EXCHANGER

RELATED APPLICATIONS

This application claims priority from USSN 60/087,530, incorporated by reference herein in its entirety.

FIELD OF INVENTION

The invention relates to methods and apparatus for counter-current exchange of gases between liquid and gaseous phases. More particularly, the invention relates to an extracorporeal gas exchanger for concentrating dissolved O_2 in a total liquid ventilation medium while reducing the CO_2 metabolic byproduct generated during each respiratory cycle.

BACKGROUND OF THE INVENTION

Liquid breathing is a therapeutic methodology currently under development for the treatment of respiratory disorders. The therapeutic protocol is based on utilizing liquid media as a mobile phase carrier solvent to facilitate transport and exchange of dissolved oxygen and carbon dioxide when brought into proximal communication with lung alveoli.

The viability of liquid breathing as a clinical treatment concept has been enhanced with the advent of perfluorocarbon (PFC)-based fluids and the recognition that their intrinsic physical properties make them ideal candidate liquids. One notable member of this chemical family, Perflubron ($C_8F_{17}Br$, LIQUIVENT™) is biologically inert (non-toxic), chemically stable (non-biotransformable), possesses low surface tension, and in combination with favorable wettability and flow characteristics, permits ease of entry into the microstructures of the lung without instigating washout of lung surfactant or introducing other undesirable side effects.

Perflubron's high CO_2 and O_2 dissolution capacity (solubility) makes possible the delivery of these respiratory gases in concentrations sufficient to mediate exchange by way of favorable transport gradients with blood levels. Perflubron's vapor pressure is positioned optimally such that treatment-end evacuation and clearance of residual liquid occurs naturally (passively) through normal evaporation at physiologic temperatures .

The efficacy of liquid breathing is being investigated and developed along two distinct lines. In Partial Liquid Ventilation (PLV), the patient's lungs are gradually instilled with PFC, while respiration is mechanically regulated in well established gas ventilator fashion. Over the course of treatment, compensatory doses of PFC are added to account both for evaporative loss and the effect of increased lung volume (functional capacity) as new lung surfaces are recruited.

Total Liquid Ventilation (TLV) is a variant modality in which a predetermined inspiratory (tidal) volume of PFC, properly dosed with dissolved oxygen, is administered endotracheally into the lung. The liquid is then subsequently withdrawn during an expiratory stage, is cleansed of CO_2 , and re-oxygenated via extracorporeal gas exchangers, before being re-administered for the next inspiration cycle.

Implicit in the TLV protocol is the requirement for a specialized gas exchange device which can efficiently replenish the liquid media on time scales commensurate with the breathing cycle. Since each lung model mandates a different volumetric dosing prescription, based upon functional lung volume, lung compliance, and the type, extent and severity of the pathological condition, the operational integrity of the device should not be compromised by potentially wide ranging liquid delivery rates. The gas exchange device is a vital and essential element of TLV therapy, and its operational performance is intimately connected with successful treatment outcome.

The extracorporeal gas exchange device used in TLV is responsible for concentrating dissolved O_2 in the PFC liquid media, while at the same time eliminating the CO_2 metabolic byproduct generated during each respiratory cycle. The relatively short time duration between inspiration and expiration cycles, the varying PFC flow rates required to meet the respiratory needs of differently sized patients, in combination with the high affinity CO_2 has for the liquid media, places unique demands on the functional requirements for gas exchange devices.

The gas exchange devices currently used in the art (i.e., spray-bubbler columns) require a finite PFC priming volume and inordinately large O_2 gas flows to effect its current level of performance. Such a gas exchange process, when scaled-up to handle larger PFC flow rates, would in-turn require correspondingly more priming volume and O_2 consumption, ultimately making treatment cost prohibitive. This would become an obstacle to future investigational use as well. A reduction in both priming volume and O_2 gas flow requirements would make treatments more economical.

The current gas exchange device used in TLV, the spray-bubbler column, is a relatively long vertical tube, in which gas and liquid make direct contact. PFC liquid is introduced at the top of the column through a nozzle and gas enters the bottom of the column through a porous septum. In such an arrangement, the interfacial area for gas exchange is generated by two mass-transfer subsystems, a nozzle, which creates a liquid dispersion, and a porous septum, which creates an air dispersion. The effectiveness of both subsystems are problematic in that their operational performance is strongly dependent on flow rate.

Both the nozzle and septum perform best at a single characteristic flow rate or narrow range of flow rates. Neither subsystem is capable of dynamically responding to varying flow rates and, as such, consistent predictable levels of performance cannot

be guaranteed. Accordingly they are not ideally suited to TLV therapy where PFC liquid flow rates can vary from one patient to another.

The nature of a nozzle is such that its mass transfer effect is dependent on the fluid dynamics, the shape and other subtle characteristics of the spray. Small variations in either flow rate, orifice diameter or nozzle shape can have dramatic effects on the fluid dynamics of the spray thereby introducing sensitive mass transfer dependencies. Because of this, nozzles are notoriously difficult to characterize.

The effectiveness of a porous septum may be even more dependent on gas rate. The gas flow rate through a septum generally dictates the size and number of bubbles created. The narrow operational range of effective gas flow rates permitted through a porous septum is limited on the lower end of the range by the requirement that for good performance the whole septum surface should bubble more or less uniformly, and on the high end of the range by the onset of serious coalescence at the surface of the septum, resulting in poor dispersion. There is a gas rate at which coalescence begins to reduce the effectiveness of dispersion and in the specific context of the PFC liquid, the rate of coalescence is more pronounced due to the high density and low surface tension issues previously described.

Since the behavior of the nozzle and the septa are both difficult to predict, empirical approaches must be used to characterize a spray-bubbler. It is therefore difficult to scaleup this device to handle larger flow rates.

In addition, the spray bubbler generally requires a finite PFC priming volume and inordinately large O_2 gas flows to effect its current level of performance. Because of the large gas flows required to remove CO_2, the oxygen flow rate must be relatively high so as to maintain the desired partial pressure of oxygen at the gas inlet. The scrubbing gas requirements being tied to the oxygenation gas requirements force artificially high levels of O_2 to be used. Such a gas exchange process, when scaled-up

to handle larger PFC flow rates, requires correspondingly more priming volume and oxygen consumption, ultimately making treatments cost prohibitive.

To date, the full therapeutic benefits of TLV have not been realized and experimental trials have been limited to small animal subjects due to apparent performance shortcomings with current gas exchange devices. This investigational impediment is primarily the result of poor mass-transfer efficiencies inherent in current device designs, the deleterious effects of which become more pronounced at the higher PFC liquid flow rates deemed necessary to properly ventilate larger animal models.

Not only is oxygen dosing of the liquid media essential, but of equal importance, and perhaps more demanding, is the design challenge of reducing CO_2 concentrations to near zero levels (complete cleansing) before reintroduction to the patient subject. Failure to do so leads to less than optimal ventilation conditions, and the resulting consequences can be serious.

Therefore, a need exists in the art for new and better methods of gas exchange between liquid and gaseous phases and particularly for devices suited to TLV therapy where PFC liquid flow rates can vary from one patient to another.

OBJECTS OF THE INVENTION

It is therefore an object of the present invention to provide an effective device and method of gas exchange, in a gas-liquid contacting environment well suited to CO_2 removal, with superior interfacial area per unit volume exposure sufficient to promote mass-transfer by mechanisms of molecular diffusion, and in addition to satisfy the scaleability and performance buffering requirements and other physical constraints involved with TLV therapy.

It is another object of the present invention to provide a device and method for use as a TLV gas exchanger wherein high efficiency CO_2 removal is achieved.

It is also an object of the present invention to provide functionally independent, repeatable unit structures, each effectively promoting gas exchange that can be readily multiplied to scale up a gas exchanger to meet the requirements of larger patients.

Potential changes in the physiological needs of patients who are enrolled in TLV therapy require that the gas exchange device be capable of processing the liquid media with equal, uncompromising efficiency in reactive anticipation to altered conditions of liquid delivery. Therefore, it is a further object of the present invention to provide a gas exchanger that dynamically scales or dynamically activates a suitable assembly of available unit structures based on the flow demand imposed by a widely variant patient base.

Frequent changes in the physiological needs of patients who are subjected to TLV liquid breathing procedures require that the gas exchange device be equipped with enough "built-in" flexibility to allow interactive control, adjustment, and regulation of the respiratory gas concentrations administered. Therefore, it is a further object of the present invention to provide a gas exchanger device that allows the clinician or patient to exert interactive operator control over the gas exchange process so as to make the device a responsive therapeutic tool.

Evaporative loss of fluid priming volume during the time-course of treatment is important from both a procedural and an economic point of view. Therefore, it is a further object of the present invention to provide a gas exchanger device that controls and minimizes such losses so as to make treatments more economical and eliminate the need for the clinician to constantly monitor fluid levels and periodically interrupt treatment to make necessary fluid additions.

Cleansing gas 'exhaust' from the device is a potential loss point since it most likely contains PFC in the form of vapor. Therefore, it is a further object of the present invention to centralize exhaust gases to allow efficient vapor recovery techniques including condensation of vapor so that condensate can be recovered and returned directly to the system.

These and other objects of the invention will become apparent to those of skill in the art upon review of the specification and appended claims.

BRIEF DESCRIPTION OF THE INVENTION

The gas exchange devices and methods described herein are based on the principle of the generation or formation of a finely divided liquid dispersion throughout a gas phase. One manner for uniformly dispersing the liquid, such that the process can be predictably scaled and respond to varying liquid flow regimens is to cast the liquid dispersion in the form of a plurality of discrete thin planes, each being finely divided (i.e., into liquid droplets), the number of which can be increased, as required, with substantial functional independence from the effects of adjacent planes.

Invention devices and methods provide means for gas exchange with very little priming volume requirement, as well as providing for efficient CO_2 removal in a one-pass operation which is scaleable to accommodate a variable patient population, and for which it is possible to dynamically respond with minimally varying operational efficiency to varying flow requirements within a treatment regimen.

The presently preferred embodiments of the invention described herein comprise a series of vertically aligned rotating disks, upon which shear-thin PFC liquid flows before generating uniform discrete thin planar liquid dispersed layers

with high interfacial contact area sufficient to promote efficient mass transfer of dissolved gases.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic representation of a preferred embodiment of the present invention.

Figure 2 is a schematic representation of a preferred embodiment of the diverter of the present invention.

Figure 3 is a schematic representation of an alternative embodiment of the present invention.

Figure 4 is a schematic representation of a preferred embodiment of the present invention as part of a closed-circuit ventilation device.

DETAILED DESCRIPTION OF THE INVENTION

In accordance with the present invention, there is provided a device for exposing a liquid to a gas for the purpose of effecting an exchange of gases between the liquid and gas phases, said device comprising:

a) a gas containment chamber having one or more ports for said gas to enter and exit said chamber,

b) an inlet for said liquid,

c) an outlet for said liquid,

d) one or more dispersion units for forming discrete thin planar layers of said liquid, located within said gas containment chamber, and in fluid communication with said source of said liquid.

Liquids contemplated for use in the practice of the present invention will typically be suitable for use in a fluid breathing treatment regimen. Such liquids include perfluorocarbons (PFC) such as Perflubron (sold under the name of LIQUIVENT), and the like.

In one embodiment of the present invention the device comprises a fluid feed tube in operative or fluid communication with the liquid inlet and the source of liquid. In a preferred aspect, the fluid feed tube is centrally located along the interior of the gas containment chamber. In more preferred embodiments, the fluid feed tube is rotatable around its longitudinal axis and has at least one dispersion unit attached thereto. For example, the dispersion unit may comprise one or more disks mounted on the fluid feed tube. In a presently preferred embodiment, there are a plurality of dispersion means mounted along a vertical fluid feed tube, wherein the feed tube has one or more outlets (orifices) associated with each dispersion unit; in this manner the dispersion means can be controllably actuated (for example by turning on or off outlets from the fluid feed tube) in response to changing liquid flow rates.

As used herein, "dispersion units" or "fluid dispersion units" means any apparatus that can be employed to form discrete thin planar dispersion layers of liquid. Thus, the present invention is not limited to the specific use of rotating disks to form the discrete thin planar liquid dispersion layers. Other potential devices and methods for droplet formation, as described herein, can be equally as effective and are contemplated for use in the practice of the present invention. Examples of such devices and methods are described herein in greater detail.

In a presently preferred embodiment, a plurality of disks are employed as the dispersion unit. The disks can be made of any suitably rigid and polished material provided that the surface does not substantially interrupt two dimensional flow of a liquid thereon. Presently preferred disks are mylar film, for example 8.5 cm diameter

floppy disks, which are lightweight (to reduce vibration during high rpm rotation), thin (to reduce edge effects and allow for close stacking of disks), polished (to minimize interruption of two dimensional flow), disposable, and reproducible (because floppy discs are manufactured with consistency). Of course, a wide variety of materials other than mylar may be utilized in the practice of the present invention. Suitable alternative materials will have the appropriate characteristics of structural integrity, wettability, surface tension interaction with the liquid, and the like. Those of skill in the art will appreciate that a number of suitably rigid materials that are lightweight and can be polished to achieve a smooth surface could be used, such as various plastics, metals or metal alloys, composite materials, and the like.

Mylar film from 3.5 inch floppy diskettes was chosen for use because of the exacting specifications and tolerances with which it is produced. The finely polished surface provides uniformity so that liquid flow fields are not perturbed by surface irregularities. By design, and in accordance with the present invention, droplets are generated in a thin 2-dimensional plane where cross contamination or interference of adjacent disk's flow fields are minimized. Successful predictable scaleup is best achieved with thin two-dimensional (independent) planes of droplets. Due to the thin nature of mylar film, edge effects on droplet formation are minimized and closer stacking arrangements are possible. The air stability and apparent rigidity of the disks as they are made to rotate aids in the formation of very thin 2-dimensional liquid dispersed layers. Perhaps the most important factor contributing to small uniform droplet formation is the manner in which the PFC liquid coats or adheres to the mylar surface. The light weight mylar material also reduces the load on the motor and less vibration is encountered at high rotational velocities.

One premise upon which a presently preferred embodiment of the present invention was built is that of dynamic performance buffering. Accordingly, it is presently preferred that considerable attention be given to the central feed tube so as to carefully balance fluid distribution over the disk assembly so that no more than a

predetermined maximum flow is delivered per unit time to any given level. This is desirable to comply with the requirement that each layer of dispersed fluid function as a linearly independent (isolated) cleansing unit and that the system as a whole respond with cleansing efficiencies minimally coupled to flow rate.

Independent experiments verified that a single disk can effectively generate small uniform droplets at moderate disk rotational velocities and with flow rates of no more than a maximum amount of about 100 ml/min. Another series of simple experiments served to define the appropriate pin-hole (orifice) sizing and vertical inter-layer spacing by observing flow distributions in tubes without disks; such values are provided herein as these elements are discussed in greater detail.

When fluid is fed axially down the centrally aligned rotating feed tube, the highest pressures occur at the bottom due to hydrostatic forces. As a result, the lowest disk in the assembly experiences the greatest pressures and fluid flows through the small orifice(s) aligned with this lowest level. As this level achieves its maximum flow value, resistance to flow builds pressure to the point where the path of least resistance is now through the orifice(s) aligned with the adjacent level above. In effect, a queuing-buffering system is created where the lowest level handles flow rates up to the maximum fixed amount and any flows in excess of this are then served by the next highest level, and so on. Flow paths may not distribute in such an idealized discrete cutoff fashion but rather are shared in accordance with continuous paths of least resistance (Hydrostatic partitioning). There is, indeed, a practical upper-limit flow rate which can be achieved through any given pin-hole orifice and, at these maximal flows, the additional hydrostatic contribution (due to gravity effects), to the total pressure is negligible in comparison to the pressures involved at each pin-hole orifice due to high pumping pressure. Preferably, in order for this effect to be predictable, the dispersion units (e.g., disks) should be evenly spaced on the fluid feed tube. Visual observation confirms this behavior: a 10 disk assembly evenly distributes fluid over each disk when flows reach 1 liters per minute (LPM) and a 15

disk arrangement was observed to balance with all disk contacting at flows near 1.5 LPM.

In another embodiment of the present invention, the dispersion unit comprises a shaped element such as a small solid half-sphere, or the like, disposed axially about the fluid feed tube and attached thereto. In this embodiment, the shaped element is partially immersed within the liquid. Upon rotation, a film forms which climbs up to the equator of the half-sphere before departing in the form of droplets. Through proper sizing and/or shape alteration, optimal dispersion and droplet formation can be achieved. For example, cone shaped and funnel shaped objects may also be semi-immersed and rotated in this manner with great effect. Funnel shaped or gravity-well shaped objects permit both sides of the surface to be utilized to first form a thin film and then launch droplets of the liquid.

In accordance with another embodiment of the present invention, particularly those embodiments wherein dispersion means are attached to the fluid feed tube, an outlet in the fluid feed tube is provided in close proximity to the dispersion means (e.g., near the upper surface of the disk). It may also be preferred for some dispersion units (e.g., a disk) to provide a diverter mounted on the dispersion means or on the fluid feed tube. The diverter in the invention device controls the access of fluid exiting the outlet(s) of the fluid feed tube to the upper surface of the dispersion means. During operation, the fluid feed tube rotates, thereby passing fluid through the fluid feed tube and out one or more outlets (orifices), resulting in the dispersion of the liquid along the upper surface of the dispersion means, from which the liquid is ejected by means of centrifugal force into the gas surrounding disk, so as to form a two-dimensional liquid dispersion in the gas. It is presently preferred that the liquid ejected in the form of discrete planar layers proceed towards the sidewalls of the gas containment chamber, ultimately colliding therewith.

Those of skill in the art will recognize that a variety of feed tube outlet sizes can be employed depending on the particular fluid chosen, the velocity of rotation and the disk material employed. When the presently preferred rotating mylar disk dispersion unit is employed, it is presently preferred that the orifice size be about 0.041 inches in diameter.

At certain rotational velocities, the rotational motion of the disk assembly was found to enhance and induce air circulation to a level where effective removal of CO_2 from the fluid was accomplished passively using room air without the need for an active cleansing gas-feed.

In other embodiments of the present invention, in order to further leverage the observed benefits of this induced circulation effect, propellers of varying pitch may be placed at several selected vertical positions on the central feed tube. The increased air circulation effect is significant in that CO_2 removal from the PFC liquid media is increased. It is evident that maintaining the CO_2 levels within the chamber to very low levels is desirable to take full advantage of the interfacial exposure developed by the liquid dispersion. This observation leads to the conclusion that, once the liquid is sufficiently dispersed in the form of small uniform liquid droplets, the air-space CO_2 concentration becomes the rate limiting step governing the overall performance of the process. As such, further efforts to more finely disperse the liquid or efforts aimed at increasing contact time are expected to be fruitless in such an air-space environment. Because of the importance of this finding, in accordance with additional embodiments of the present invention, there are provided means for improving air circulation.

One of the objects of the present invention is to not only remove dissolved gases (e.g., CO_2) but to exchange them for other gas or gases (e.g., O_2). Accordingly, in a presently preferred embodiment, substantially pure oxygen gas is supplied by a flat plate bubbler directly to the bulk liquid that has temporarily pooled and collected at the bottom of the contacting chamber before exiting. This method proves adequate

and O_2 gas requirements following such treatments were found to be minimal. Indeed, the O_2 gas requirements were found to be reduced from those demanded by current spray-bubbler columns since extra oxygen need not be supplied to compete with the much higher gas turn-over required for CO_2 removal. In other embodiments of the present invention, the bulk liquid pool is directed into a separate compartment from that of the upper air space, as shown in Figure 1 (which is specialized for CO_2 removal) thereby resulting in more efficient oxygenation. While only certain embodiments of oxygenation devices and methods are shown and/or described herein, many alternatives may be conceived by those of skill in the art, and are properly contemplated as within the scope of the present invention. Further examples of such techniques and devices are provided below.

The great freedom of choice in which practitioners of the present invention may configure the size, shape and geometry of the contact chamber, the various methods which may used to generate scaleable PFC liquid dispersions, in addition to embodiments described herein that are designed to enhance air circulation, affords great flexibility to those skilled in the art in practicing the invention.

Because the invention device described herein, in all its embodiments, is particularly suited to efficient mass transfer between a liquid and a gas, in accordance with another embodiment of the present invention, there are provided methods for promoting efficient mass transfer between a liquid and a gas, said methods comprising:

creating a plurality of finely divided uniform liquid dispersions containing a first dissolved gas, wherein the uniform liquid dispersions are each in the form of a discrete thin planar layer, and

sequentially contacting a continuous gaseous counter-current flow containing a second gas with the plurality of finely divided uniform liquid dispersions.

Because it is desirable to practice invention methods in a manner that accommodates a variety of patients and treatment regimens, in another embodiment of the present invention, the number of discrete thin planar layers is increased proportionally with increase in the flow rate of the incoming gas, thereby rendering the efficiency of mass transfer of the first and second gases into the opposite phase substantially independent of the flow rate of the incoming gas flow.

Because invention methods are well suited to transfer of gas between gas and liquid phases, such methods are well suited to liquid breathing regimens. Accordingly, in another embodiment of the present invention, the first gas is carbon dioxide and the second gas is oxygen. In still another embodiment of the present invention, the liquid is a perfluorocarbon and the gas is air.

It is most desirable that the thin liquid dispersion layers generated in the practice of the present invention not interfere with one another in a manner that would impart disorder to the associated liquid droplets. Accordingly, it is presently preferred that each discrete planar layer functions substantially independently from adjacent layers.

When the gas phase is maintained with near zero partial pressures of CO_2, and the individual fluid elements (e.g., PFC droplets) making up the planar dispersion of liquid are allowed sufficient contact time with the gas, favorable gradients for diffusion persist until equilibrium is reached between the gas and liquid phases. Accordingly, in another embodiment of the present invention, the partial pressure of carbon dioxide in the gas contacting the droplets making up the dispersions in the first of the plurality of thin planar layers contacted is near zero.

It is to be understood that the following alternative embodiments may be used either alone or in various combinations to achieve the desired effects. The precise description used in no way is intended to limit the embodiment to that description, but

rather is intended to convey and include other means and methods which have essential equivalence within the spirit and scope of the invention.

Modifications to Inner Chamber Walls

It is recognized that air circulation plays an important role in the operation of the invention device. While the above-described rotating dispersion unit assembly was found to induce efficacious air flow by virtue of its motion, there are a series of embodiments of the invention device that, either alone or in combination, may leverage this motion to maximize the desired effect.

Inclusion of a baffle or thin blade, affixed to the gas containment chamber wall either vertically positioned, or in other suitable orientations, promotes mixing of the gas phase (e.g., air), within the chamber. Static baffles or blades affixed to the inner chamber wall induce whirlpool-like mixing as air moves in the annular space between disks and chamber wall. The baffles may be solid continuous, perforated, or sectioned to protrude at selected locations with the chamber. The baffles do not necessarily have to be attached to the chamber's inner surface but may alternately be freely suspended or supported by appropriate means.

When the disk assembly rotates at relatively high velocity, substantial circular air-flows are induced within the chamber. In an effort to improve air-circulation in the vertical (top to bottom) direction to ensure adequate mixing and ventilation, gently curved or spiral shaped baffles or the like could be installed within the chamber. The circular air-flows would then be directed upward or downward by the preferential blocking action or interference with such baffles.

Air vents or pores at the chamber periphery, or anywhere on the top or bottom surface of the chamber, combined with a negative pressure sink for gas removal, can be used to draw fresh air into the chamber in an evenly distributed fashion, depending on the positioning and quantity of the air vents employed. Presently, it is preferred

that the vents are slanted or otherwise oriented to prevent the liquid from exiting the gas containment chamber other than through the intended liquid outlet(s). Other distributed gas inlets, one-way valves, or the like may be employed to accomplish the same effect.

Modification to the Chamber Environment

Of importance to air flow is the manner in which gas is introduced into the chamber. Accordingly, in another embodiment of the present invention, positive pressure sources can be used to force gas into the chamber. Alternatively, sub-atmospheric pressure devices, or the like can be used to draw gas out of the chamber.

In one embodiment of the present invention, air circulation may be further enhanced by placing a cage or grid-like structure fitted internally within the gas containment chamber for strategic placement of air flow ports for either positive or negative pressure flows. Such an enhancement of air flow can be used either alone or in combination with other embodiments described herein.

The gas containment chamber may be fashioned to act like a bellows. As the dispersion unit assembly is made to rotate, a bellows, flexible bag, pumping diaphragm, or the like may be synchronized appropriately to collapse and expand with frequency, thereby drawing air into this gas-liquid contacting volume. Use of one-way flap valves or other suitable valves permits this bellows action to preferentially draw air into the chamber.

An oscillating top plate and/or accordion-like chamber walls can also be used to provide freedom of movement for the bellows-like chamber to expand and contract, also drawing air into the chamber. In an alternative embodiment, the up and down motion of a piston or syringe-like plunger, either internal or external to the chamber, combined with one-way valves could be used to rapidly flush the air-space.

In the so-called bellows embodiment, the gas containment chamber can be made of a simple bag-like, balloon-like, or otherwise flexible or elastic bladder with a thin collapsible surface, optionally contained within a rigid support structure. The bag can be kept inflated with a mild positive air pressure. When the liquid is not being fed, the rotation of the dispersion unit assembly can be stopped, and the bag can collapse partially or entirely, to flush air out before being rapidly inflated for the next liquid feed cycle. This action primes the air space before each liquid feed. The dispersion unit assembly rotation can be halted between inspiration and expiration cycles when the liquid is not being fed. Flexible or elastic materials used as the contacting chamber provide the benefits of being disposable and easily permit variable volume operation. Accordingly, while not in use, the chamber occupies little space.

Alternatively, the contact chamber can be made to telescope (e.g., a cylinder within a cylinder) so as to expand or contract either to promote air flow or to allow the adjustment of the height of the chamber and hence its volume. Such a telescoping chamber is easy to size to accommodate the needs of various patients.

The gas containment chamber can be connected to a mechanical ventilator to precisely regulate air flows into and out of the chamber during a treatment. Such a scheme can be used to deliver the precise volume and concentration of gas mixtures into the chamber. This scheme may be used alone or in combination with any other embodiments described herein.

In another embodiment of the present invention, the gas phase environment is maintained with near zero partial pressures of CO_2. By allowing the individual fluid droplets (e.g., PFC droplets) making up the planar dispersion sufficient contact time, favorable gradients for diffusion persist until equilibrium is reached, at which time liquid phase CO_2 concentrations can be made to approach the desired low levels. In similar fashion, if gas phase partial pressures of O_2 are appropriately adjusted, the

liquid phase should become oxygenated to near equilibrium partial pressures of O_2 with those in the gas phase.

Adornments to Dispersion Units

In the presently preferred embodiment exemplified in Figure 1, the upper surface of each dispersion unit (i.e., disk, in the embodiment illustrated in Fig. 1) is brought into direct contact with liquid. The bottom surface however remains available for the inclusion of adornments in relief, fins, vanes, or other such protrusions of various angles, pitches, and placements. The rotational motion of dispersion units equipped with such adornments will induce air flow and reduce points of stagnation between dispersion units. Also the fins could be attached to the periphery of all or some of the dispersion units in the assembly. Either etched or pitted surfaces could also be used to drag air along with rotational motion. Of course, the adornments to the underside or periphery of the dispersion units should not be made in such a way so as to cause the dispersion units to flutter as they rotate as fluttering might cause the liquid to be dispersed in a chaotic fashion and/or not be restricted into planes or zones that are isolated from interference with droplets for adjacent planes or zones.

Additions to Rotating Feed Tube

In alternative embodiments of the present invention, objects that augment gas flow with properties similar to, but not limited to, propellers, impellers, paddle agitators, fans, turbines, or blades of various pitch, are placed in one or more positions below, above, or interspersed at selected vertical positions within the dispersion unit assembly and affixed to the rotating shaft of the feed tube to increase air circulation (see, e.g., Fig. 3, where an exhaust fan **124** is attached to the feed tube). These objects may be rigid or flexible to accommodate the airflow generated by specific embodiments of the dispersion unit. The rotation of such objects may be engaged by attachment to the feed tube shaft or rotation may be caused independently by attachment to externally supplied forces (e.g., motors, hydraulic impellers, and the

like). Placement of such objects for movement of gases within a concentric draft tube may be employed to create an artificial chamber for top to bottom mixing of gas flow within the gas containment chamber. Fan blades, or the like can also be placed below the top plate of the gas containment chamber or gas containment outside the chamber above the top plate to augment gas flow.

Modifications to the Feed Tube

The advantages of counter-current flow in mass transfer are well recognized. While true counter-current flow is generally difficult to achieve in liquid-in-gas dispersions, the unique geometric uniformity of the dispersion of the liquid phase in devices and methods according to the present invention provide opportunities to achieve such counter-current flow wherein the gas is encouraged to move in directions opposite to that of the liquid droplets which comprise the thin planar units of dispersed liquid. Accordingly, in one embodiment of the present invention, the central axis of rotation acts as a sink for the gas phase. In this embodiment, at each level where a dispersion unit resides a gas port or orifice is positioned to draw gas out of the chamber, thereby inducing air to flow horizontally across each dispersion unit in the dispersion unit assembly. To accomplish this goal, for example, the fluid feed tube can have a region, inter-lumenal, multi-lumenal, or otherwise, devoted to gas flow. Alternatively, two or more tubes, which orbit around the same axis, one which delivers liquid and one which draws air out, can also be utilized for this purpose.

If the negative pressure sink is created uniformly along the axis of rotation, pseudo counter-current air flow is induced. The highest concentrations of dissolved gas (e.g., CO_2) to be removed from the liquid phase can be found near the central tube where the liquid phase first meets the dispersion unit surface (initial contact position). Sub-atmospheric pressure sources preferentially remove CO_2 in this region before it becomes mixed and diluted throughout the chamber. Pores located at the chamber periphery can be used to draw fresh air coaxially inward, first making contact with the cleanest liquid droplets in true counter-current fashion.

To further enhance this counter-current embodiment of the invention, zones of restricted air flow can be artificially created using the thin horizontal disks in the dispersion unit assembly. The disks serve to compartmentalize each discrete, thin planar layer, of liquid dispersion. As long as the droplet flight path is not interfered with, the thin cross-sectional air-spaces created by the disk assembly within the chamber provide for improved air flow management by eliminating vertical cross flows. True counter-current flow can be achieved with the appropriate negative pressure sink at the axis of rotation.

It is a particular feature of this embodiment of the invention device and method that when horizontal disks, for example, are employed, the overall process does not become a stage-wise operation wherein the same liquid contacts each disk. Each spinning disk creates a gas zone that is isolated from adjacent gas zones so as to conform with the paradigm of functional independence and allow for predictability of function and results during scale-up. The use of disks in the invention device provides for greater management of gas flow because the cleansing gas is used more efficiently with less evaporative effect over that of a single bulk, well mixed air space.

Fluid Distribution Embodiments

It will be recognized by those of skill in the art that fluid distribution plays an important role in the practice of the present invention. The following embodiments provide means to enhance or promote appropriate fluid distribution.

Inter-Disk

In a presently preferred embodiment of the invention, for example as illustrated in Figure 1, fluid distribution from the feed tube to any particular disk is achieved by way of specially constructed flow diverters (i.e., inter-disks) positioned above each dispersion unit in the dispersion unit assembly. Other methods or materials can be

used to achieve a similar effect. For example, fibrous, foam-like, swab-like, sponge-like, or other similar materials can be used to dissipate the velocity of the liquid jets emanating from the central feed tube, thereby functioning to gradually leak fluid onto each associated dispersion unit in a controlled fashion and at the appropriate initial contact position. Wire mesh, screen-like, cloth-like, or other similar material can also be used to accomplish this purpose. Such objects may be selected to accommodate closer dispersion unit spacing. A small circular semi-flexible flap, for example made of mylar, can be positioned near the center shaft to dissipate the velocities of jets entering the chamber, either due to its compliance or by surface tension sealing/leaking.

Intra-Dispersion Unit

In a presently preferred embodiment of the present invention, fluid feed among disks or dispersion units is accomplished by way of a central rotating feed tube. It is possible to use other methods to achieve the same effect. For example, the PFC liquid can be introduced into the feed tube from either the top or bottom of the vertical tube. Fluid can also be fed through tubes aligned parallel and along sides of a center shaft. In this embodiment, the center rotating shaft would not need to be hollow. Alternatively, fluid can be fed through a manifold, so that each dispersion unit has a dedicated tube aligned perpendicular to the center shaft which extends into the dispersion unit assembly for the purpose of depositing liquid onto the initial contact position. Other means for introducing fluid feed include using a rotating screw (e.g., an Archimedian screw, or the like) to move liquid through the center tube and onto each dispersion unit.

An Archimedian screw may also be inserted into the hollow feed tube to draw fluid from the bottom of the chamber upward to a point wherein the fluid is then brought into contact with each unit in the vertical dispersion unit assembly. In another embodiment, the same screw is used to recycle fluid which collects at the bottom of the chamber for a second pass, permitting an internal recycle

mode as required for effective gas transfer into and/or out of the fluid. In this embodiment, fluid no longer needs to be fed through the central hollow tube, but rather can be introduced into a preferably cylindrical walled-off region near the bottom chamber. This isolated region near the bottom of the feed tube is the entry point for the fluid, which is drawn upward by Archimedian action. Fluid that has been dispersed and cleansed would then be collected outside the walled-off region for subsequent oxygenation, as required.

In another aspect of invention intra-disk fluid distribution, holes or perforations in the disk surface may be utilized to allow fluid to drain down onto successive disks.

In a preferred embodiment of the present invention, as exemplified in Figure 1, hydrostatic forces are used to distribute fluid in a partitioning scheme based on flow rate and vertical height. Since each dispersion unit has a given vertical height, the hydrostatic variation between dispersion unit is fixed by virtue of this height. To alter the hydrostatic partition effect without changing dispersion unit spacing can be accomplished by tilting the contact chamber, for example, to reduce the effective vertical direction. Since the spinning dispersion units operate in any near-vertical orientation, the axis of rotation can be tilted without substantial impairment of the dispersion process. A degree of freedom can be built into the device to allow for such orientational flexibility.

Alternative Embodiments of Dispersion Units

As discussed above, "dispersion units" or "fluid dispersion units" means any apparatus that can be employed to form discrete thin planar dispersion layers of liquid. Thus, the present invention is not limited to the specific use of rotating disks to form the discrete thin planar liquid dispersion layers. Other potential devices and methods for droplet formation, as described herein, can be equally as effective and are contemplated for use in the practice of the present invention. Examples of such devices and methods follow.

Centrifugal Shear-Thinning Type

For example, shapes other than disk made of various materials, rigid or otherwise, such as cones, funnels, perforated plates, etched or dimpled surfaces, and the like, can be used to shear-thin fluid streams and produce droplets, provided that the fluid sufficiently adheres to the surface of such material and that the transition to droplets occurs in non-chaotic fashion. Various stacking arrangements of these alternative embodiments are also possible.

Film Forming Semi-Immersion Type

In another embodiment of the present invention, rotation of shapes, other than disks, that are semi-immersed in fluid can effectively promote formation of droplets. For example, when a small solid half-sphere partially immersed within PFC liquid is rotated, a film of fluid forms thereon and climbs up to the equator of the half-sphere before departing in the form of droplets. Through proper sizing or choice of shape, optimal dispersion and droplet formation can be achieved. Cone shaped and funnel shaped objects have also been employed in this manner with great effect. Funnel shaped or gravity-well shaped objects may also be employed in the practice of the present invention, thereby permitting stacking. Moreover, both sides of the surface can be utilized to first form a film and then launch droplets in accordance with the present invention.

Jet Impingement

In another embodiment of the present invention, a scaleable discrete thin planar liquid dispersion is created using a high pressure jet impinging on a rotating sphere, toothed gear, pin-wheel, or like arrangement.

Rotating Sprayer

In still another embodiment of the present invention, a rotating hollow tube without disks can be employed for casting of droplets into a thin planar layer.

Rotating spiral armed sprayers using orificial breakup of liquid or oscillating impingement type rotating sprayers, and the like, can also be used.

Ultrasonic Means

Ultrasound may also be used in the practice of the present invention to produce one or more discrete thin planar layers of droplets. This, as with the other embodiments described herein, serves to illustrate that it is the formation of discrete thin planar dispersions of liquid droplets that is most important to the practice of the present invention, not the manner in which this is accomplished.

Ink-Jet Technology

Ink-Jet technology may also be used in the practice of the present invention to produce one or more discrete thin planar layers of droplets. Such technology is well capable of forming precisely controlled dispersions, and can be applied to form a discrete thin planar layer of droplets, or other suitable structural entity, shape or form that can be propagated with complete linear independence in three dimensions such that combinations of entities introduce no side effect or collaborative behavior other than permitting larger flow rates to be processed.

Alternative Embodiments of Scrubbing Gas

Scrubbing gas is often desirable to provide and maintain a favorable air-space environment for CO_2 interphase transport. Experiments conducted thus far in testing the present invention have used ambient room air, compressed air, or bottled oxygen as the scrubbing gas. For example, when the contact chamber was passively ventilated with room air, the high speed rotation of the dispersion apparatus assembly was found to induce air circulation patterns, thus creating a favorable air-space environment for CO_2 removal. The use of room air has the advantage of obviating the need for an active gas feed.

Scrubbing gas can be recycled and passed in a closed loop through processes which remove or absorb CO_2. Such a closed-loop embodiment enables evaporative loss to be controlled. For example, helium, or the like, can be used as a recyclable scrubbing gas, and has additional advantages where PFC vapor must be recovered from the gas exhaust. The wide disparity in density between helium gas and PFC vapor allows for effective separation techniques, as are known by those of skill in the art. If CO_2 is removed from such a helium exhaust, the helium gas can be recycled for reuse in the chamber in closed-loop fashion. Additionally, if the scrubbing gas is presaturated with PFC vapor, further net transport of PFC to the gas phase is thereby prevented.

In another embodiment of the present invention, the scrubbing gas is pre-chilled. In this embodiment, the temperature of the liquid droplets is reduced upon contact with the gas, thereby shifting the vapor pressure equilibrium conditions so as to minimize evaporation.

Of course, use of an oxygen-rich air mixture as the scrubbing gas permits oxygenation and CO_2 removal to be accomplished simultaneously by way of the same process. Other gases that have therapeutic benefits, for example gas streams containing therapeutic active agents such as antibiotics, anti-asthmatics, and the like, may also be used in the practice of the present invention.

Rotational Power Embodiments

In the presently preferred embodiment exemplified in Figure 1, a DC motor **102** is used to drive the disk assembly **104**. Such electric motors coupled to gears **106** or pulleys attached to central shaft **108** either internal or external to the chamber can be used, provided that variable speed rotation of the assembly is achieved. As will be understood by those of skill in the art, any power source can be used that is capable of imparting the high velocity rotation that is preferred for the practice of the present invention. For example, pneumatic methods of driving the disk assembly may be

employed. Indeed, the scrubbing gas feed itself or other air pressure sources can be harnessed to induce rotation of the dispersion unit assembly. For example, one or more appropriately angled gas jets emanating from an armature attached to the central feed tube can be used to force rotational motion of the dispersion unit assembly while simultaneously adding scrubbing gas to the chamber. In this embodiment of the invention, the whole assembly is optionally disposable since a motor is not required.

Use of hydraulic pressure from the PFC liquid stream to drive the rotation of the dispersion unit assembly is also contemplated for use in the practice of the present invention. When this method is employed, the life of the entire device can be prolonged because when the liquid is not being fed, the dispersion unit rotation comes to a halt. Halting the rotation of the dispersion assembly may also reduce evaporation when liquid is not being fed. Other methods for imparting rotation to the dispersion unit assembly involve the detection of fluid flow using a trip-wire or other suitable sensing mechanism that can be made to turn rotation of the assembly on or off.

In some aspects of the present invention, it may be desirable to synchronize rotation of the dispersion assembly with the patient's breathing cycle. This can be accomplished in any number of ways, including the use of control software, or other suitable means.

Droplet Collection Embodiments

As described herein, the gas exchange with the liquid is best accomplished by generating discrete thin planar dispersions of the liquid in a droplet form. Accordingly, droplet collection is an important consideration to the practice of the present invention. Droplets travel at high velocity through the gas containment chamber air-space and then collide with the chamber wall where they coalesce into bulk fluid. Very small droplets which are formed at the higher speed rotations of dispersion units collide and rebound due to their apparent rigidity (and inability to

coalesce instantaneously upon impact). Since the errant scattering of droplets should be avoided, methods are needed to reduce this rebound effect.

Therefore, in one embodiment of the present invention, shock-absorbing materials are used to line the interior of the chamber to reduce or cushion the effects of droplet impact and reduce elastic collision effects. The wettability characteristics and the fine structure of the shock-absorbing material are important to the time-scale in which droplets coalesce. Materials with protrusions and fibrous, foam, matted, or like materials are effective shock-absorbing materials and will gradually dissipate droplet momentum to the point where droplets do not rebound. In addition, or alternatively, the side walls of the chamber can be angled to direct or focus the rebounding droplets into specific more controlled flight patterns (preferably downward).

Liquid Vapor Recovery Embodiments

As discussed herein in other contexts, loss of liquid (e.g., PFC) vapors should be minimized for economic and procedural reasons. The following embodiments of the present invention provide both preventative and curative methods to reduce vapor loss during gas exchange.

In one embodiment of the present invention, vapor loss is reduced by lowering the temperature of the PFC liquid, thereby lowering the vapor pressure of the PFC liquid and the evaporative propensity of the liquid. One means for accomplishing this goal is to chill the scrubbing gas because the PFC, once dispersed in the form of droplets, has an enormous surface area exposure thereby allowing for efficient heat transfer. The PFC may be cooled prior to entering the chamber as well, although the liquid will quickly equilibrate to the temperature of the surrounding chamber air. Alternatively, or in addition, increasing the air pressure in the chamber will disfavor evaporation of the PFC liquid.

In another embodiment of the present invention that is intended to minimize loss of PFC vapors, trace amounts of one or more surface active agents (e.g., surfactants) are added to the PFC to increase rigidity and/or coat or seal the surface of droplets to prevent PFC molecules from escaping to the gas phase. It has been found that the CO_2 interphase transport is not greatly impeded due to the small size of the solute molecules. In most cases, the surface active agent is removed upon exiting the chamber unless the presence of the surface active agent in no way compromises the patient. Alternatively, dust particles, finely divided solids, or other insoluble particulate material may be used to increase the rigidity of droplet surfaces. These particulates and like materials are more readily removed from the PFC before it is recycled to the patient.

Variable rotation rate of the dispersion unit assembly may also be employed to control droplet size so as to reduce evaporative loss while still permitting effective CO_2 removal. In addition, as described herein, halting rotation of the dispersion unit assembly when liquid is not being fed will reduce the exposure of the PFC liquid to air circulation and thereby reduce its evaporation.

In another aspect of the present invention, a condenser placed either within or outside of the gas containment chamber is used to recover vapor from the gas phase. The present invention lends itself to the internal inclusion of a condenser. For example, a perforated plate type condenser unit positioned internally near the top of the gas containment chamber is provided. Typically there will also be an upper gas exhaust port near the top of the gas containment chamber. Finely meshed wire-screen or like moisture trapping material can be employed as the plate material provided that interference with exit gas flows is not compromised. Condensed PFC would then fall back into the scrubber without effecting its operation. Additionally a low speed fan could be used to remedy any stagnation of air flows in the Z-direction. This embodiment may also employ a two compartment design as described herein (i.e., a gas containment chamber and a fluid containment chamber). In this way scrubbing

gas requirements are distinct from that of oxygenation and it is no longer necessary to increase O_2 flows to keep partial pressure high enough in ever increasing scrubbing gas flows. Oxygenation can be achieved by any of the methods described herein.

If helium or other light gas is used as the scrubbing gas, a separation technique based on gravity or centrifugal force, as understood by those of skill in the art, can be used in the practice of the present invention to recover the heavier PFC vapor from the lighter gas phase.

Heat Exchange Embodiments

In accordance with the present invention, there is great freedom of choice afforded the practitioner in selecting the size, shape, and geometry of the chamber, which affords flexibility in achieving other adjunct and simultaneous goals, such as heat exchange, and the like. It may be useful, for example, as part of a TLV protocol to alter the temperature of the liquid within the invention gas exchanger device. For example, this technique may eliminate the need for separate heat exchange device(s) in the TLV circuit. The following alternative embodiments involve methods to either increase or decrease the temperature of the liquid phase used in practice of the invention.

As the PFC droplets emerge from the edge of each disk or alternative dispersion unit at high velocity, the droplets ultimately collide with the inner wall of the gas-exchange chamber. This is often an opportune time to effect the temperature of the fluid by way of heat transfer. Therefore, in one embodiment of the present invention, the outer wall of the chamber in the invention device is heated or cooled by appropriate means including, but not limited to, electrically resistive heat tape, nichrome wire, hot/cold water jacket circulator, or the like. In one aspect of the present invention, the gas containment chamber wall is made of materials with reasonable thermal conductivity characteristics, thereby allowing the gas containment chamber itself to function as a heat exchanger.

As described herein in other contexts, PFC dispersed in the form of droplets has an enormous surface area exposure for heat transfer, the most efficient heat transfer opportunity for altering the temperature of the fluid is during the time that the fluid is dispersed as small droplets. Thus, in one embodiment of the present invention, the scrubbing gas is heated or chilled, for example, just prior to entering the gas containment chamber. For a given small droplet, the surface area is very large in relation to the volume of the fluid that has to be brought into thermal equilibrium with the surrounding air. Therefore, thermal equilibrium is approached very rapidly, with the droplets almost instantaneously reaching substantially the same temperature as the surrounding gas when the heated or cooled air is brought into contact with the droplets.

Alternatively, if the chamber wall is made of or coated with (inside or outside) material having a high thermal conductivity, heat exchange can be achieved when the liquid (e.g., PFC) collects on the surface of the chamber wall after droplet collision and coalescence. To enhance this effect, an annular water jacket or similar device can be built around some portion of the outer wall of the gas containment chamber. Of course, the top and/or bottom plates of the gas containment chamber can also be made of such material. Alternatively, or to further enhance heat exchange, the thermally conductive material can also protrude into the chamber (e.g., like a cold-finger or cooling fin).

In addition, the rotating disks or alternative dispersion units can themselves be made of conductive material and/or have the temperature thereof altered by electrical resistance heating, or the like, thereby providing, for example, thin film heat exchange.

The interior-space of the chamber can also be heated by way of radiant sources, such as heat lamps, or the like. Use of appropriate heat absorption materials

in fabrication of invention devices will enhance heat exchange in this embodiment of the invention.

Oxygenation Embodiments

When oxygenation of previously "scrubbed" liquid is desired, any suitable means for oxygenating the scrubbed liquid may be employed in the practice of the present invention. In a presently preferred embodiment of the invention, pure oxygen gas is supplied directly to the bulk liquid by a flat plate bubbler as the liquid is temporarily pooled and collected at the bottom of the gas containment chamber. In this embodiment of the invention, the requirements for O_2 gas were found to be minimal. Alternative methods for achieving oxygenation of the liquid phase are also contemplated for use in the practice of the present invention.

For example, in one embodiment of the invention, those of skill in the art can achieve oxygenation and CO_2 removal in one step in a single compartment by feeding a desired flow of an oxygen/air mixture into the chamber. The gas exchange efficiency of such embodiments is not optimal, however, because the flow of the oxygen/air mixture must be maintained at such a high rate for CO_2 removal that excess oxygen would have to be added just to compete and maintain the desired partial pressures of O_2 in the scrubbing gas phase. To improve the efficiency of this embodiment of the invention wherein oxygen is used to partially replace the air in the scrubbing gas, it is desirable to localize oxygen delivery to the liquid film on the wetted wall at the periphery of the gas containment chamber. Alternatively, by lining the inner wall of the chamber with porous material from which O_2 is dispersed, a wetted-wall bubble oxygenator can be created. In yet another aspect of the present invention, as liquid flows down the sides of chamber wall in thin sheets, localized gas ports, or the like, can direct O_2 onto the surface of the descending liquid film.

In another embodiment of the present invention, exemplified in Figure 3, the bulk liquid pool is confined in a lower liquid containment compartment or chamber

126, maintained in fluid separation from the gas exchange space within the gas containment chamber. A valve or other like apparatus such as a perforated plate **128** can provide for fluid communication between the gas containment chamber and the liquid containment chamber, while preserving fluid separation between the two chambers. The upper gas exchange space is then dedicated to CO_2 removal. In a chamber having such a two compartment design, scrubbing gas requirements are distinct from the oxygenation requirements. Hence, it is no longer necessary to continuously increase O_2 flows in the scrubbing gas to keep the partial pressure of O_2 high enough to oxygenate the liquid phase. Instead, O_2-containing gas can be supplied to the lower chamber by way of a separate oxygen inlet **130**. In this two-compartment chamber, oxygenation can be independently achieved by several methods.

In one alternative embodiment of the present invention, a specially constructed oxygenator in which a sheet of porous material (made of high density polyethylene, or the like) is integrated into the bottom plate of the chamber. The porous sheet is made to cover nearly the entire cross sectional area of the chamber. Oxygen gas is fed in pressure distributed fashion by way of a recessed air-space in contact with the entire under-surface of the sheet. Bubble formation is substantially evenly distributed over the porous surface with good air dispersion and minimal coalescence at low flow rates. Since the liquid pool is relatively shallow and air flow is distributed over such a wide area, gas velocity is reduced and good air dispersion is achieved. If the fluid exit port is centrally aligned within the porous surface the natural whirlpool action creates slightly more residence time and mixing of the liquid on the porous surface, thereby providing more efficient oxygenation.

In another embodiment of the present invention, rotating gears, or the like are used to create a draw-down rotational impeller. Air is drawn down from the upper air-space of the gas containment chamber into the liquid pooled at the bottom of the

chamber where it is dispersed. In one aspect of the invention, the rotation of the gears is coupled to the rotation of the dispersion unit assembly.

As will be understood by those of skill in the art, the same types of dispersion unit apparatus employed in the gas containment chamber for scrubbing the liquid of CO_2 can be used to oxygenate the liquid. Thus, an oxygenating dispersion unit **132**, such as a disk apparatus, shaped elements, ultrasonication, ink-jet technology, or the like, can be employed as described herein. In these embodiments of the present invention, it is presently preferred to provide a separate liquid containment compartment (or "oxygenation compartment") where liquid is directed after exiting the gas containment chamber through its exit port. The same rotational feed tube could be employed to drive the dispersion units in the liquid containment compartment. In this aspect, a plug or the like is preferably placed in the feed tube to prevent mixing of the liquids in the separate compartments.

When the stacked disk embodiment is employed, the manner in which the disk assembly is configured, along with the novel approach of feeding the fluid through a centrally aligned hollow tube for subsequent distribution and hydrostatic partitioning, acts to buffer the performance of the gas-exchange process against the variations in PFC fluid flows required to treat variously sized patients. As a natural consequence, the efficiency of gas-exchange is not adversely effected by varying PFC fluid flows. The rotating disk embodiment additionally makes scaling of the device to accommodate larger animal subjects easier to achieve.

The present invention has as its underlying foundational basis the generation or formation of a finely divided PFC liquid dispersion throughout a continuous gas phase, vacuum, or rarefied gaseous region, enclosed within a bounded contacting volume of suitable size. The manner envisioned for uniformly dispersing the liquid, such that the process can be predictably scaled and respond to varying liquid flow requirements with equal efficiency, in compliance with the aforementioned necessities

of TLV gas exchange, is to cast the liquid dispersion in the form of a discrete thin plane. In addition, the present invention may be practiced using other suitable structural entities, shapes, or forms which can be propagated with complete linear independence in three dimensions such that combinations of entities introduce minimal side effects or collaborative behavior other than permitting a larger liquid flow rate to be processed. Extension of this planar dispersion notion, thereby permitting deterministic scaleup, is achieved by physical repetition (or propagation) of this fundamental gas exchange unit structure into the available third dimension such that each successive plane forms a functionally independent layer without cross-interference from adjacent layers. Independence is desired so as not to introduce second order or non-linear effects into the process. Non-linearities violate the tenets of predictability by number (i.e., scaleability).

The uniqueness of this invention is further augmented by, but not limited to, a novel performance buffering construct in which the promotion of a variably changing number of discrete thin planar liquid dispersion layers occurs in dynamic fashion as flow rates are increased or decreased. Accordingly, in use, the invention device dynamically senses gas exchange demand, by virtue of fluid flow rate, and automatically makes the corresponding compensating adjustment to activate or invoke an appropriate number of the discrete thin planar liquid dispersion units, to ensure that the overall process exhibits a consistently buffered and invariant performance profile.

All U.S. and Foreign Patent publications, textbooks, and journal publications referred to herein are hereby expressly incorporated herein by reference in their entirety.

The invention will now be described in greater detail by reference to the following, non-limiting example.

EXAMPLE

Among the many possible embodiments of the invention concept, a presently preferred embodiment is exemplified in the following discussion and is represented schematically in Figures 1 - 3. This embodiment comprises a vertically oriented cylinder **100** made of transparent rigid plastic (~16 cm inner diameter by ~29 cm height). Flat plates, of similar material, affixed to both the top **101(a)** and bottom **101(b)** of the cylinder serve to enclose this gas-liquid contacting volume (gas containment chamber). Housed within this chamber is an assembly comprising a series of thin mylar film disks **104** (~40 μ thick and ~3.5 inch diameter) uniformly stacked on a centrally aligned fluid feed tube **108** (~0.25 inch OD) about which high speed rotation is made to occur. Between each disk are positioned specially constructed spacer-diverters **110** (~1 cm high) which are designed to deposit fluid onto the upper surface of each disk and ensure uniform initial contacting as the fluid feed makes its way through two pin-hole size orifices **112** located on the fluid feed tube vertically coincident with each disk. A center hole in the top plate and a bearing assembly **114** anchored to the bottom plate, both aligned with the intended axis of rotation **116**, act to center and stabilize the disk assembly as it rotates within the chamber. High speed rotation of the disk assembly is achieved by a gear assembly **106** external to the chamber which is attached to, and concentric with, the feed tube. This gear in turn is engaged by a small variable speed DC motor **102** (e.g., 6-24 V) with matching gears.

The presently preferred embodiment exemplified in Figure 1 also shows a gas inlet tube **118** where cleansing gas is fed into the chamber at various flow rates. This feed tube, being adjustable, allowed the air flows to be directed at specific vertical and axial positions within the chamber. Other gas feed embodiments that may be used include multiple feed tubes, each with evenly spaced jets made to vertically coincide with the liquid dispersed layers, and the like. Similarly, the depicted embodiment

shows a liquid outlet **120** where the scrubbed liquid can exit the chamber (typically, the liquid will enter the chamber through an inlet connecting the liquid source with the fluid feed tube).

Continuing with an example of a preferred embodiment, initial fluid contact at each disk is accomplished with a specially designed spacer/diverter. The essential features of the diverter are shown schematically in Figure 2, where fluid feed direction is indicated with bold arrows. Two pin-hole size orifices **112** (preferably about 0.041 inches diameter), cut into opposite sides of the feed tube **108** and located vertically coincident with the recessed annular region of the diverter **110** provide a contiguous path for the inlet fluid stream to reach the upper surface of the disk **122**. The annular recessed region provides space for orificial jet velocities to dissipate by impinging on the inner wall of the diverter. PFC is then directed downward where it first makes contact with rotating disk through a slightly elevated open skirt at the bottom of the diverter. The radial component of the liquid's velocity is effectively reduced, thereby achieving the desired velocity-dissipated, centrally-aligned initial condition upon contact of the fluid with the disk.

Continuing with an example of a preferred embodiment, once the continuous bulk liquid is deposited onto the disk at its initial contact position, it is then exposed to the centrifugal acceleration induced from high speed rotation, creating a shear-thinned film of fluid. The thin liquid film adheres to the disk material (which is preferably mylar) through the surface molecular forces which exist between the mylar and liquid, and those between the liquid molecules themselves. The strength of these frictional forces allows the liquid film to attain a substantial radial velocity as it is accelerated from its initial rest condition to the periphery of the disk. A 2-dimensional liquid dispersion of small, uniformly sized, droplets is then produced as the fluid first separates into thin transient filaments which persist momentarily and ride along the periphery of each disk before breaking into droplets. Due to the high radial velocities attained at the periphery, the droplets are ejected tangentially upon

departure and travel with high velocity through the air-space of the chamber with minimal gravitational deflection.

It will be recognized by those of skill in the art that the thin liquid film first formed on the surface of a rotating disk likely contributes to gas exchange. Although probably not the predominant mechanism, such gas exchange is contemplated as within the scope of the present invention. Such a liquid film is readily scaleable and may have applicability to TLV (without the necessity of combining it with other embodiments of the present invention).

At no point in the mechanics of this dispersion process is impingement breakup of liquid used to create droplets. The resulting chaotic and errant scattering of droplets would contravene the goals of the 2-dimensional dispersion notion of the present invention. The method employed, by design, is to bring liquid into relatively gentle initial contact with each disk ensuring a velocity dissipated, centrally aligned initial condition.

With the appropriate rotational velocity, the liquid in air dispersion generated by the rotating disk assembly provides sufficient gas-liquid interfacial surface area to ensure efficient removal of dissolved CO_2 from PFC fluids.

While the invention has been described in detail with reference to certain preferred embodiments thereof, it will be understood that modifications and variations are within the scope and spirit of that which is described and claimed.

THAT WHICH IS CLAIMED IS:

1. A device for exposing a liquid to a gas, said device comprising:

a) a gas containment chamber having one or more ports for said gas to enter and exit said chamber,

b) an inlet for said liquid,

c) an outlet for said liquid,

d) one or more dispersion units for forming discrete thin planar layers of said liquid, located within said gas containment chamber, and in fluid communication with said source of said liquid.

2. A device according to claim 1, wherein said gas containment chamber comprises a flexible material.

3. A device according to claim 1, wherein said gas containment chamber comprises internal surface features or internal attachments for mixing said gas.

4. A device according to claim 1, wherein the inner walls of said gas containment chamber comprise an apparatus for delivery of said gas to portions of the liquid located proximal to said walls.

5. A device according to claim 4, wherein said apparatus comprises a wetted-wall bubble oxygenator.

6. A device according to claim 1, wherein said dispersion units comprise a shaped element, an ink-jet type fluid distributor, or an ultrasonic means.

7. A device according to claim 6, wherein said shaped element is shaped as a disk, a semi-sphere, a cone, a funnel, a gravity well or a concave arc.

8. A device according to claim 1, wherein said fluid communication is provided by a fluid feed tube located centrally in said gas containment chamber.

9. A device according to claim 8, wherein said fluid feed tube is rotatable about its longitudinal axis.

10. A device according to claim 9, wherein said dispersion units is/are attached to said rotatable fluid feed tube.

11. A device according to claim 10, wherein said dispersion units:

a) are axially disposed about said longitudinal axis of said fluid feed tube,

b) are shaped elements selected from a semi-sphere, a cone, a funnel, a gravity well, or a concave arc, and

c) are partially submerged in a pool of said liquid,

wherein rotation of said feed tube and attached dispersion units causes said fluid to be directed along the surface of said dispersion units towards its widest point from which it is ejected as a discrete thin planar liquid dispersion to contact the walls of said gas containment chamber.

12. A device according to claim 9, wherein said fluid feed tube has one or more fluid outlets for directing the liquid to said dispersion units.

13. A device according to claim 12, wherein:

a) said dispersion units comprise one or more disks,

b) said fluid outlets each comprise a pin-hole orifice, and

wherein rotation of said feed tube and attached disk(s) causes said fluid to be directed along the upper surface of said disk towards its peripheral edge from which it is ejected as a discrete thin planar layer.

14. A device according to claim 13, wherein said one or more disks are made of mylar.

15. A device according to claim 13, wherein said one or more disks have one or more protrusions or adornments in relief on a bottom surface.

16. A device according to claim 13, wherein each of said disks has an associated diverter such that liquid exiting from said fluid feed tube is directed to an upper surface of said associated disk.

17. A device according to claim 16, wherein said diverter is skirt-shaped and axially disposed about said longitudinal axis of said fluid feed tube above each associated disk, wherein liquid exiting said orifices initially contacts the inside of said skirt shape and is thereby directed towards said upper surface of said associated disk.

18. A device according to claim 16, wherein said diverter is a sponge-like or cloth-like material that temporarily absorbs the liquid exiting said orifice, and, upon saturation, passively dispenses said liquid onto said upper surface of said associated disk.

19. A device according to claim 1, wherein said liquid collects in the bottom of said gas containment chamber after contacting the sides thereof.

20. A device according to claim 8, wherein said liquid is recirculated from the bottom of said gas containment chamber into said fluid feed tube.

21. A device according to claim 19, wherein said liquid is oxygenated while resting in said bottom of said gas containment chamber.

22. A device according to claim 21, wherein said oxygenation is carried out by means of a flat plate bubbler located at or near the bottom of said gas containment chamber.

23. A device according to claim 1, wherein said liquid is directed from said dispersion units to the side walls of said gas containment chamber, and wherein said liquid is subsequently oxygenated.

24. A device according to claim 23, further comprising:

e) a fluid containment chamber in fluid communication with said gas containment chamber, said gas containment chamber having a fluid exit port for said liquid,

wherein said liquid is directed from said dispersion units to the side walls of said gas containment chamber and subsequently through said fluid exit port of said gas containment chamber into said fluid containment chamber.

25. A device according to claim 24, wherein said liquid is oxygenated within said fluid containment chamber.

26. A device according to claim 1, wherein said liquid comprises a perfluorocarbon.

27. A device for exposing a liquid to a gas, said device comprising:

a) a fluid feed tube in operative communication with a source of said liquid, wherein said fluid feed tube is rotatable around its longitudinal axis;

b) one or more disks mounted on said fluid feed tube;

c) one or more outlets in said fluid feed tube in close proximity to the upper surface of said disk(s); and

d) a diverter mounted on said disk or on said fluid feed tube, wherein said diverter directs said fluid exiting said outlet to said upper surface of said disk;

wherein said device, when operated by rotating said fluid feed tube and attached disk(s) and passing fluid through said fluid feed tube and out said outlet(s), results in the dispersion of said liquid along said upper surface of each of said disks and into a gas surrounding said disks, so as to form one or more discrete thin planar liquid dispersions in said gas.

28. A device according to claim 27, further comprising:

e) a container surrounding said fluid feed tube in three dimensions so as to encapsulate said fluid.

29. A device according to claim 27, wherein said outlet is a pair of pin-hole size orifices in said fluid feed tube.

30. A device according to claim 27, wherein said device comprises a plurality of disks.

31. A device according to claim 30, wherein there is a pair of orifices in said fluid feed tube for each of said plurality of disks.

32. A device according to claim 30, wherein said disks are evenly spaced on said fluid feed tube, and wherein said disks are used serially as the flow of fluid through said device is increased.

33. A device according to claim 28, further comprising:

f) an air pump that causes gas flow into and out of said container.

34. A device according to claim 27, further comprising means for inducing counter-current air flow against the direction of motion of said fluid.

35. A device for exposing a liquid to a gas, said device comprising:

a) a fluid feed tube operably associated with a source of said liquid, wherein said fluid feed tube is rotatable around its longitudinal axis;

b) an outlet in said fluid feed tube;

c) a collector mounted on said fluid feed tube in close proximity to said outlet, wherein the fluid exiting said outlet pools in said collector; and

d) a shaped element mounted on said fluid feed tube;

wherein said device, when operated by rotating said fluid feed tube and passing fluid through said fluid feed tube and out said outlet, results in the formation of a fluid film along a lower surface of said shaped element, and then the dispersion of said liquid from said shaped element into the gas surrounding said device, so as to form a discrete thin planar liquid dispersion in said gas.

36. A device according to claim 35, wherein said shaped element is shaped like a cone, funnel, gravity-well, semi-sphere, or concave arc.

37. A method for promoting efficient mass transfer between a liquid and a gas, said method comprising:

creating a plurality of finely divided uniform liquid dispersions containing a first dissolved gas, wherein the uniform liquid dispersions are each in the form of a discrete thin planar layer, and

sequentially contacting a continuous gaseous counter-current flow containing a second gas with the plurality of finely divided uniform liquid dispersions,

wherein the number of discrete thin planar layers is increased proportionally with increase in the flow rate of the incoming gas, thereby rendering the efficiency of mass transfer of the first and second gases into the opposite phase substantially independent of the flow rate of the incoming gas flow.

38. A method according to claim 37, wherein the first gas is carbon dioxide and the second gas is oxygen.

39. A method according to claim 37, wherein each discrete planar layer functions substantially independently from adjacent layers.

40. A method according to claim 37, wherein the partial pressure of carbon dioxide in the gas contacting the droplets making up the dispersions in the first of the plurality of planar layers contacted is near zero.

41. A method according to claim 37, wherein the liquid is a perfluorocarbon and the gas is air.

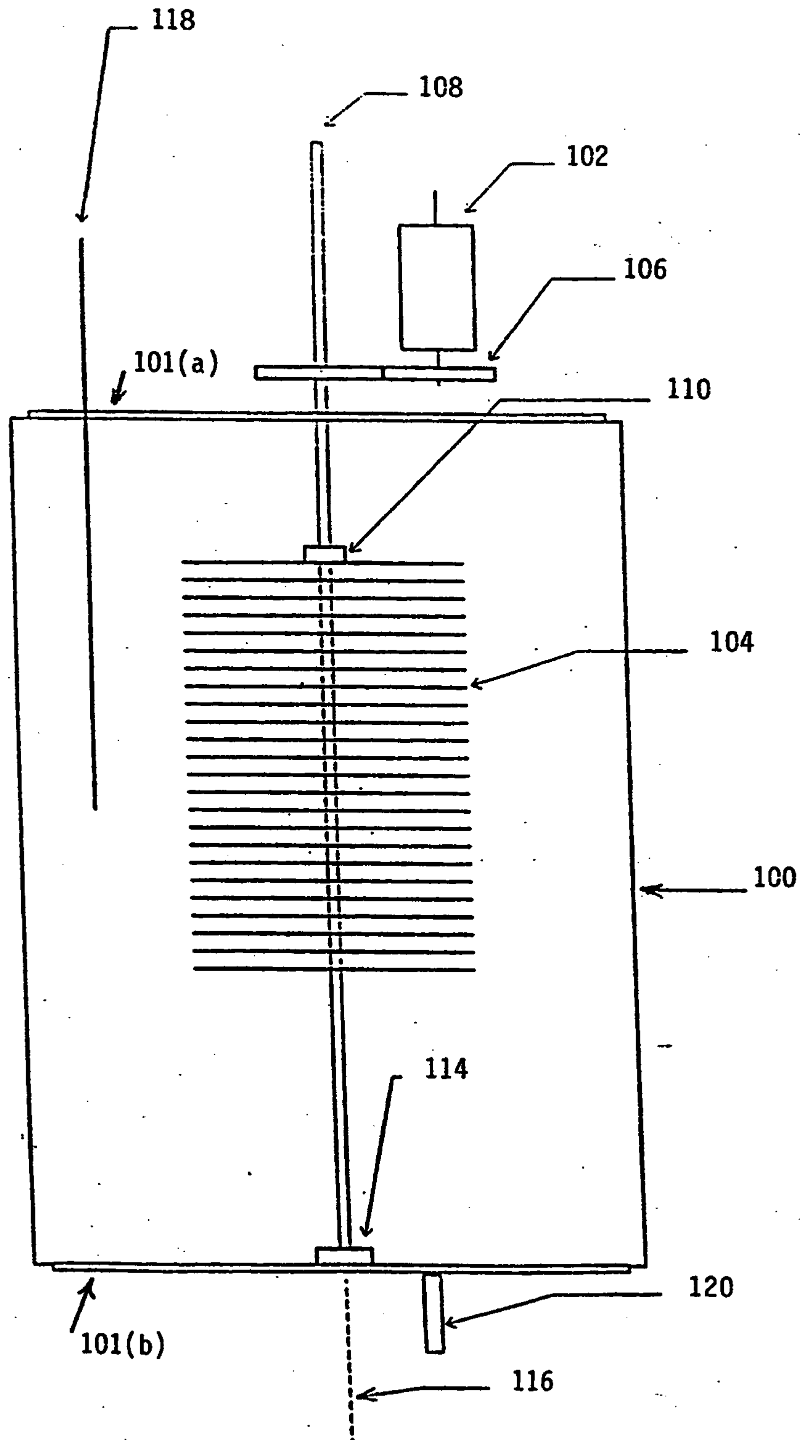


FIGURE 1

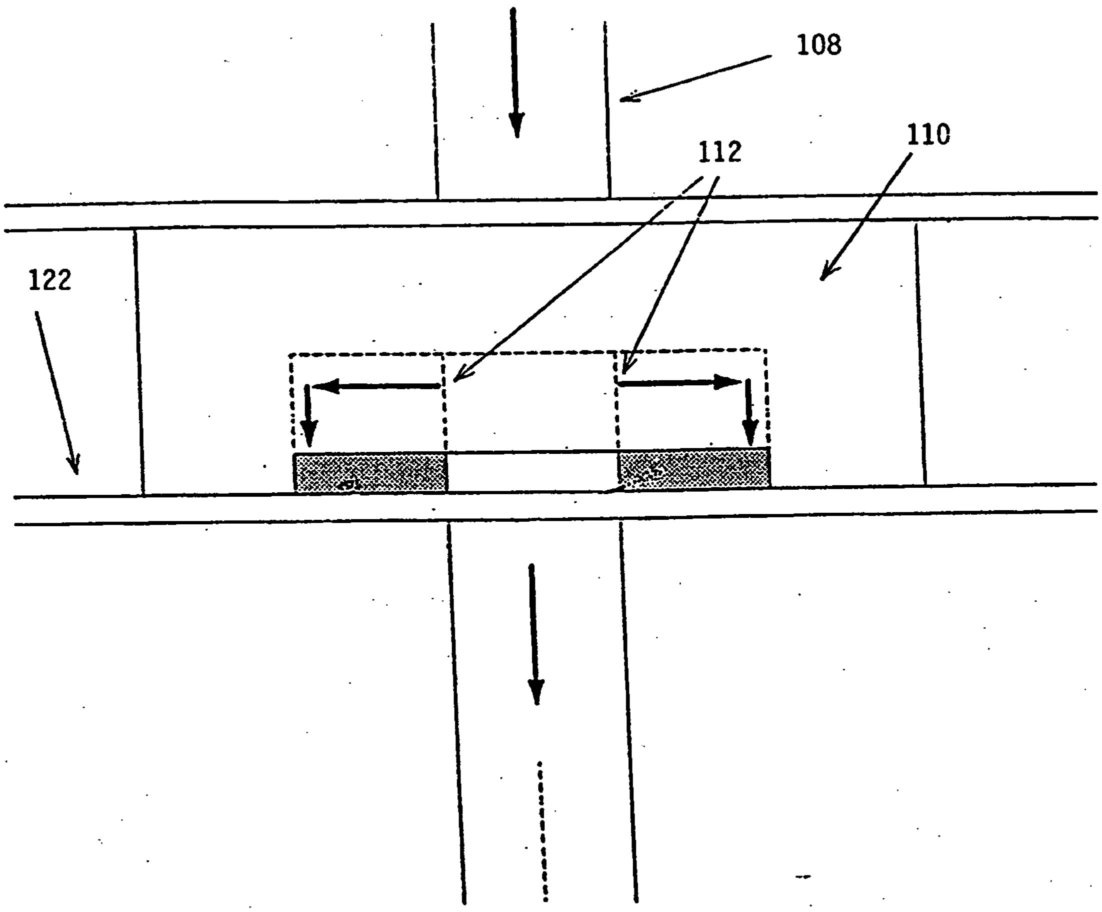


FIGURE 2

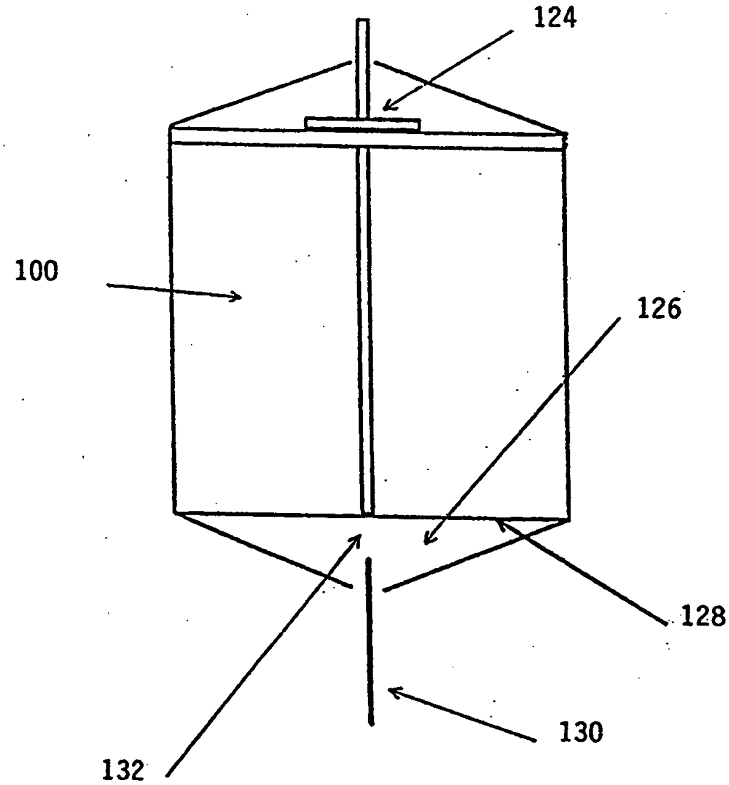
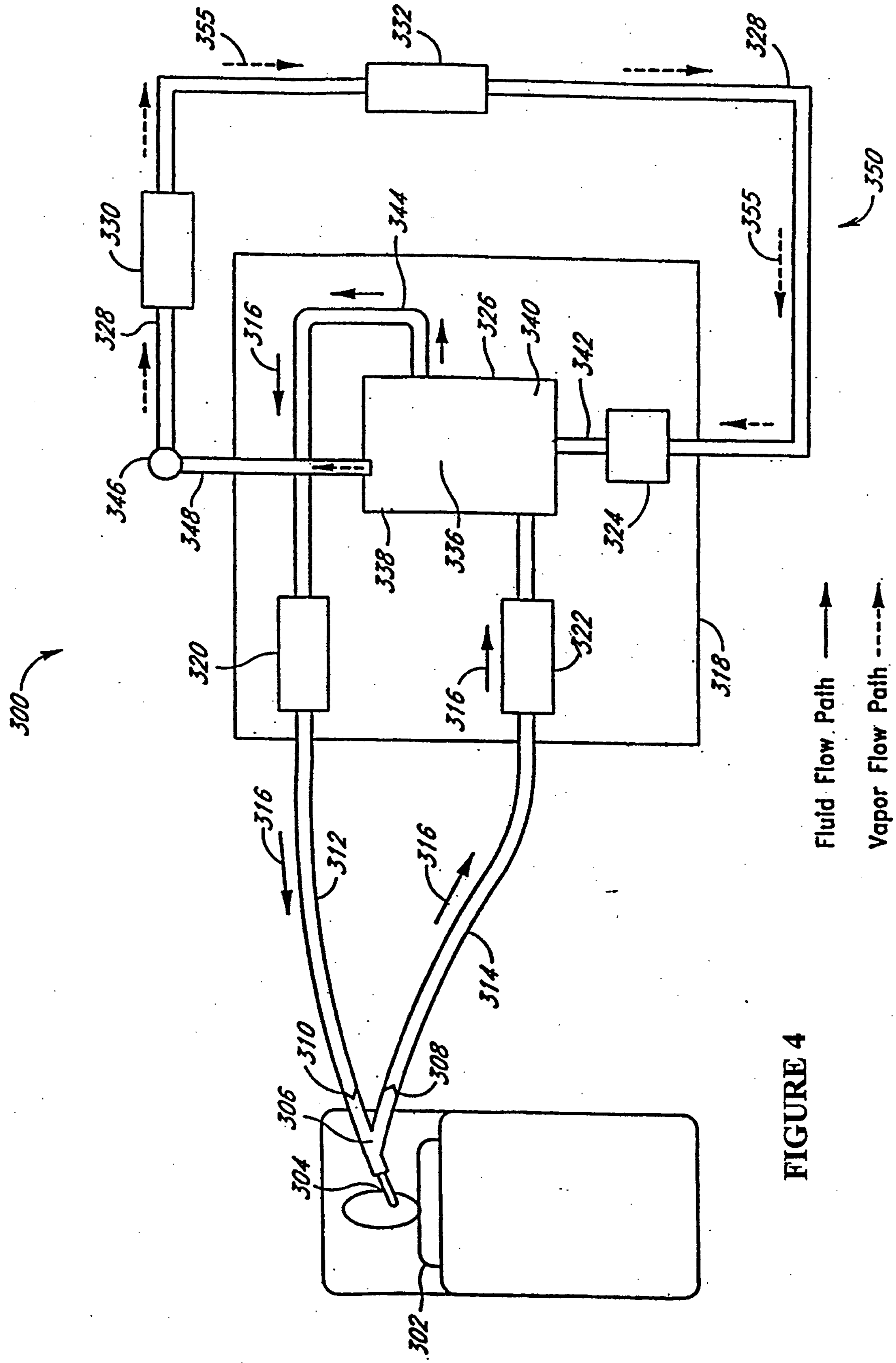


FIGURE 3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Fluid Flow Path
Vapor Flow Path

FIGURE 4

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/12132

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 B01F3/04 B01F7/26 A61M16/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 B01F A61N A61M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 2 113 562 A (ICI PLC) 10 August 1983 (1983-08-10)	1-4,6-8, 11-13, 15,19, 20,27-36
Y	the whole document	5,21-26, 37-41
Y	WO 97 19719 A (ALLIANCE PHARMA) 5 June 1997 (1997-06-05) the whole document	5,21-26, 37-41
X	US 5 226 727 A (REICHNER THOMAS W) 13 July 1993 (1993-07-13) the whole document	1-4, 6-12,27, 28,30-36

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
3 November 1999	12/11/1999

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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